High Performance Long-Wavelength Quantum Dot Infrared Photodetector (QDIP) Focal Planes Operating at High Temperature

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Outline

- Motivation
- What are Quantum Dots?
- Diminishing dimensions
- QDOT IR detectors
- Dot-in-a-Well Infrared Detectors
- LWIR Focal Plane Array
- Highlight of Accomplishments
- FIR QDIP Proposal
- Summary

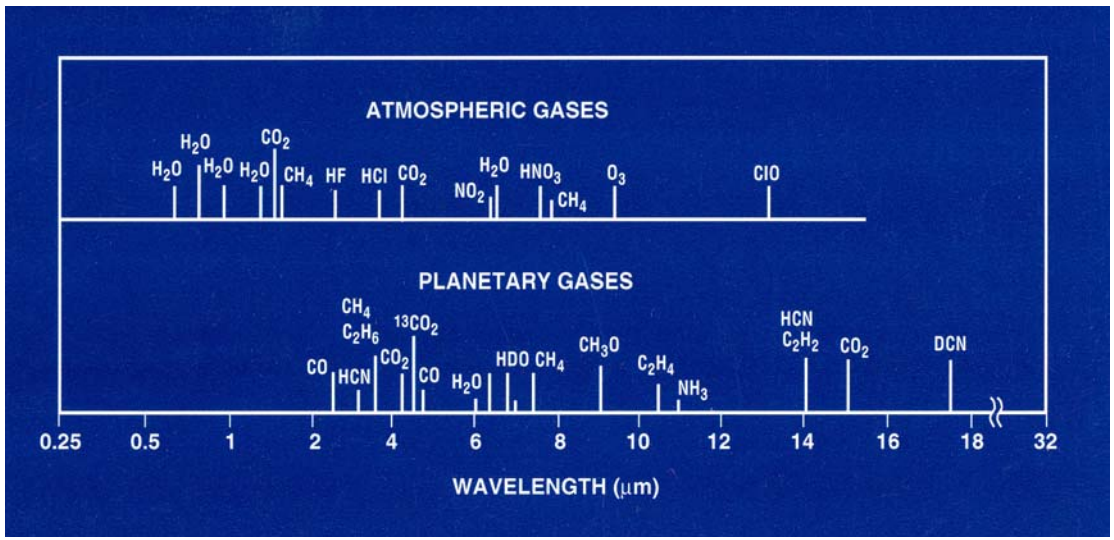
Motivation

Technology Gap:

Many applications require high performance (i.e., Quantum Efficiency >50%) large format (i.e., 2048x2048 pixels or higher) highly uniform (i.e., uniformity > 0.02%) mid-wave and long-wave infrared focal plane arrays operating above 100K.

Applications:

Astronomy, Earth & planetary remote sensing, Pollution monitoring, Night vision, Target recognition, Surveillance, Stand off detection of remote chemicals agents, IED detection, Quality control, Service & maintenance industry, medicine, etc.

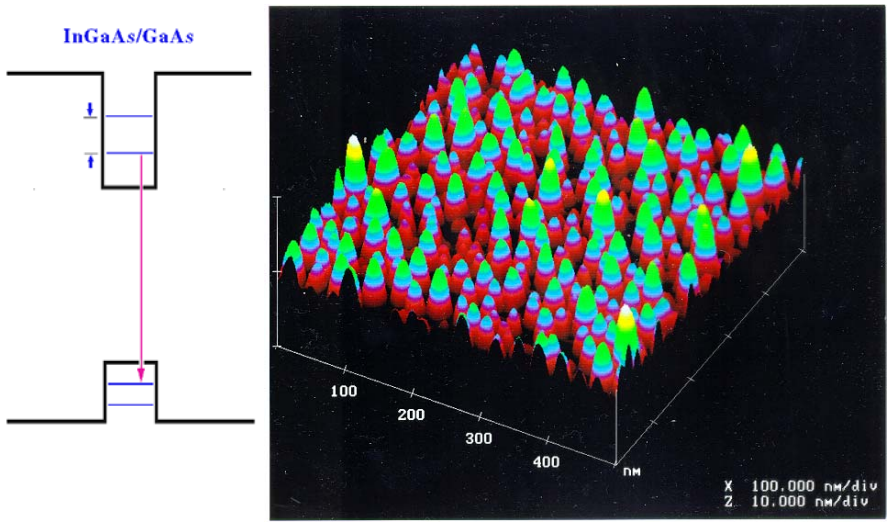


ABSORPTION SPECTRA OF SOME GAS MOLECULES

VISIBLE IR

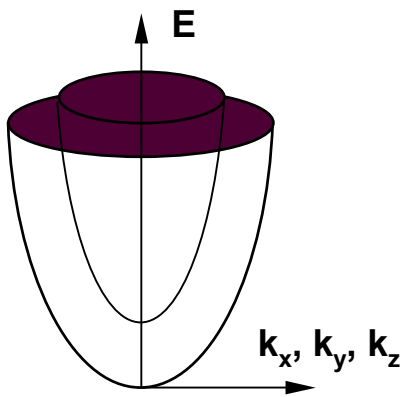
What Are Quantum Dots?

Quantum dots are very small semiconductor structures (nanometers or tens of nanometers in diameter) surrounded by a material of a wider bandgap. They confine electrons and holes in three spatial dimensions and to a very small number of energy levels, depending on their size. They respond very efficiently to particular wavelengths of light.



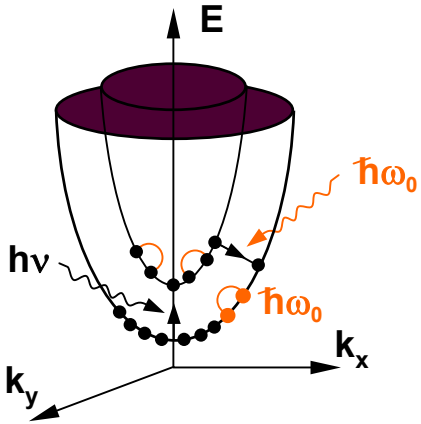
Quantum dots (QDs): structures capable of confining carriers in three dimensions

Diminishing Dimensions



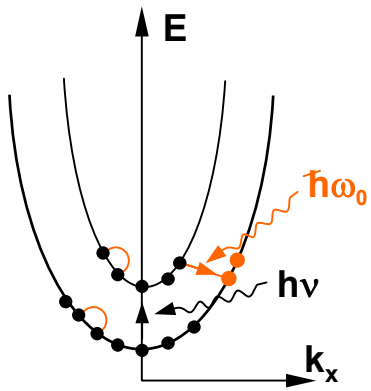
Bulk

$E = k_x^2 + k_y^2 + k_z^2$



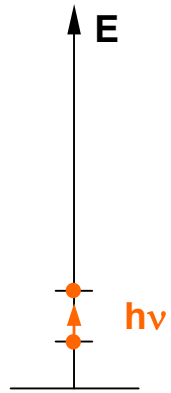
Quantum Well

$E = k_x^2 + k_y^2 + E_l$



Quantum Wire

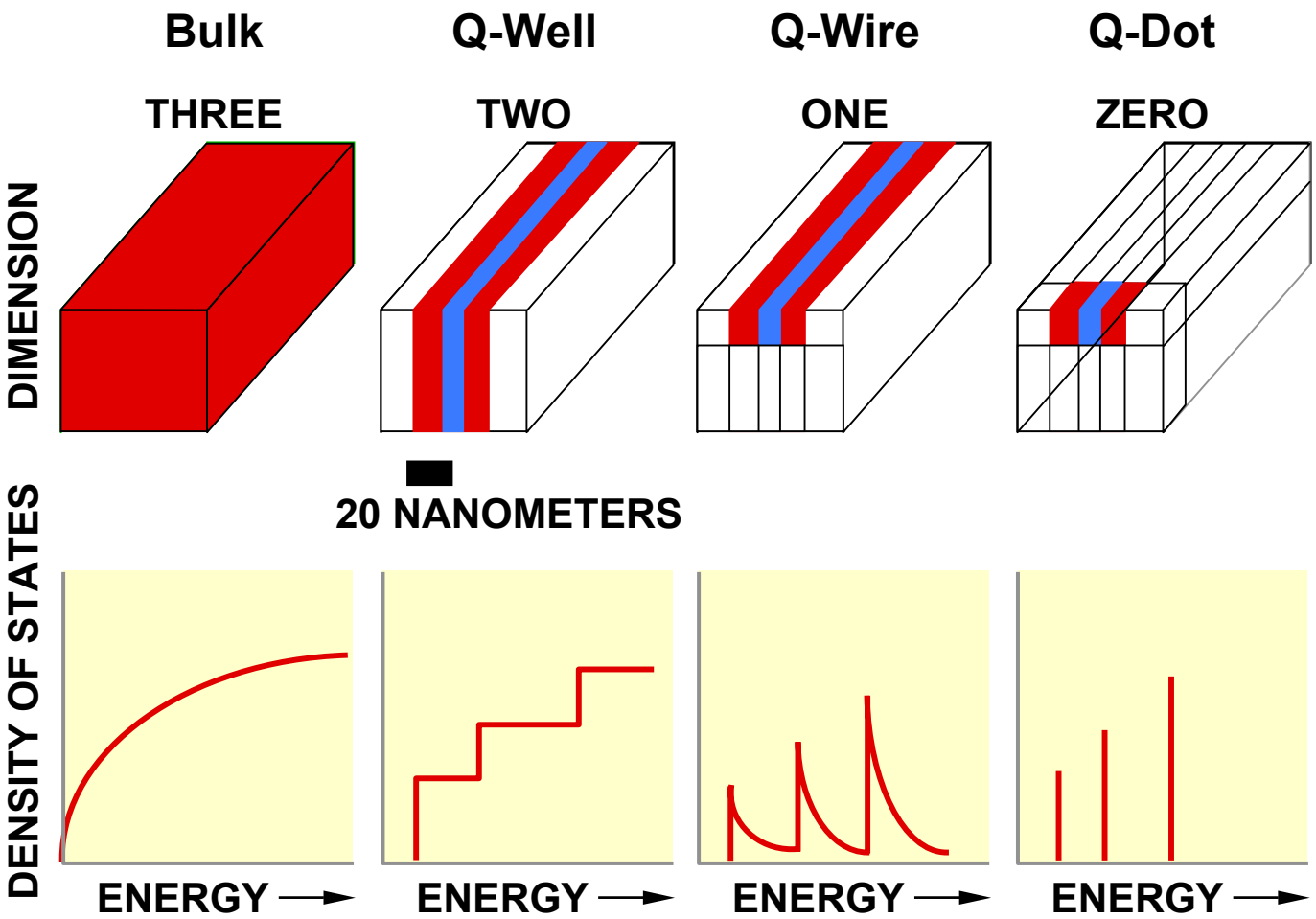
$E = k_x^2 + E_{l,m}$



Quantum Dot

$E = E_{l,m,n}$

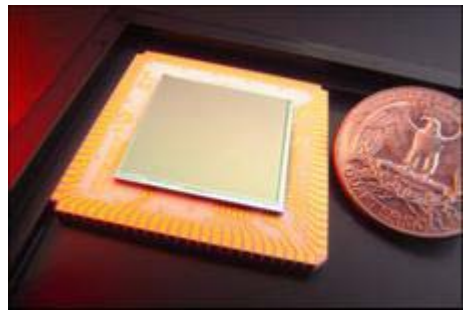
Density of States



Energy levels in quantum dots are discrete.

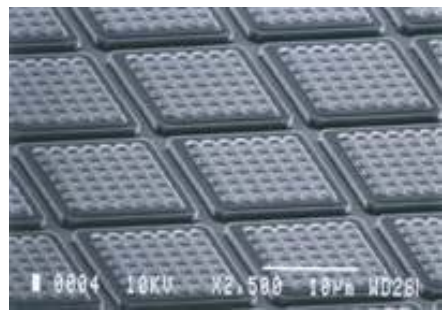
Quantum Dot Based LWIR FPAs

- ✓ Build on JPL's proven track record of delivering infrared FPAs based on quantum effects in III-V photodetectors
  - Large format
  - Excellent uniformity
  - Excellent operability
  - Low 1/f noise
  - Thinned arrays eliminate
    - Optical crosstalk
    - Thermal mismatch with ROIC
    - Pixel delamination



1024x1024 MWIR FPA
Designed, grown, and fabricated at JPL

- \+ Add quantum dots to this current capability
  - Normal incidence absorption
  - Higher temperature operation (lower dark current)
  - Higher responsivity (longer lifetime)
  - Further increase the radiation hardness



Individual pixels in an FPA, with integrated grating structure

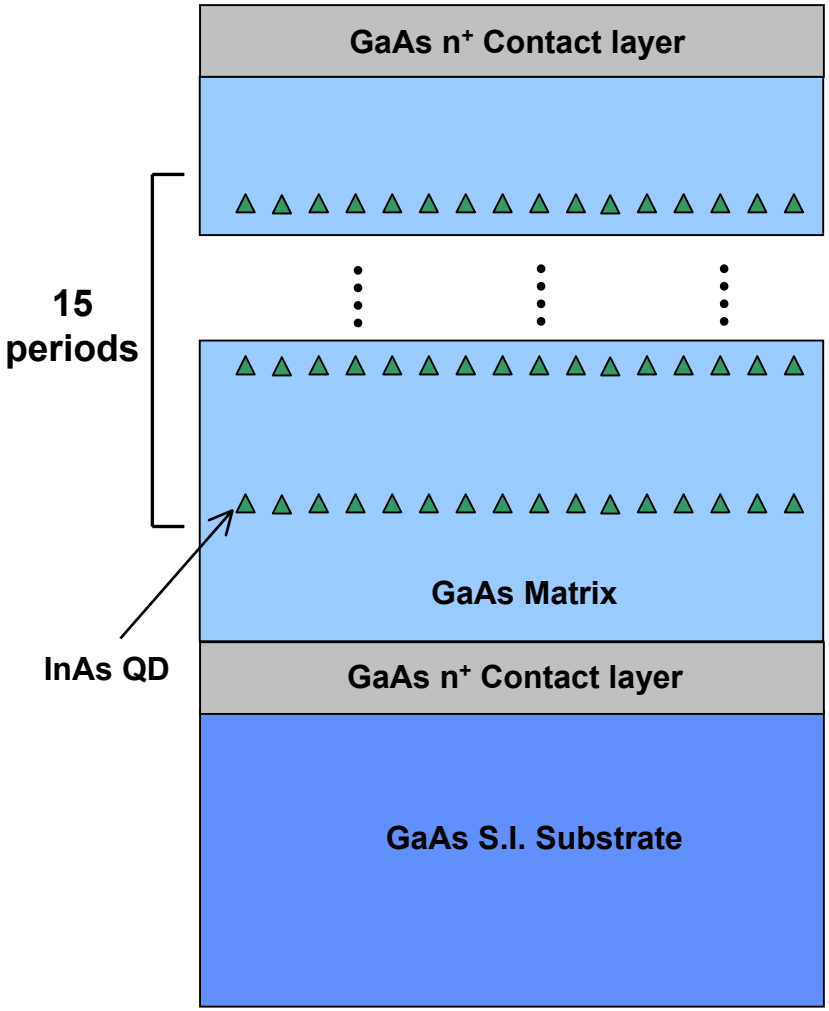
- = New generation of high performance high operating temperature infrared focal plane arrays

Objective

	Objectives	Achieved
Spectral Response	10-12 μm to 10-13 μm	8-11 μm
Quantum Efficiency	30% to 60%	15% absorption QE, 300K ~20% normalized to 77K
Detectivity (D*)	$1x10^{11}$ Jones @ 100K	$1x10^{10}$ Jones @ 77K
Array	32x32 test array	640x512 Imaging Focal Plane Array

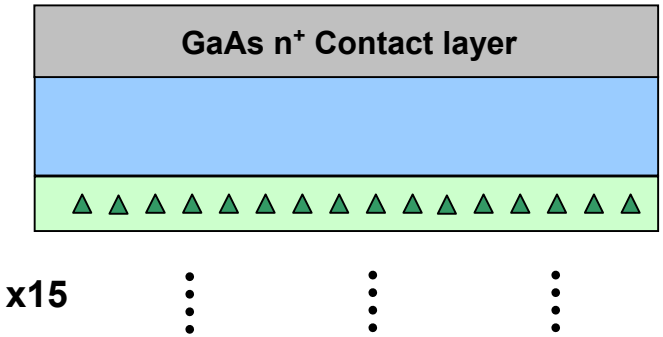
3D quantum confinement → enables normal incidence → quantum efficiency
Phonon bottleneck → increase carrier lifetime → raises operating temperature

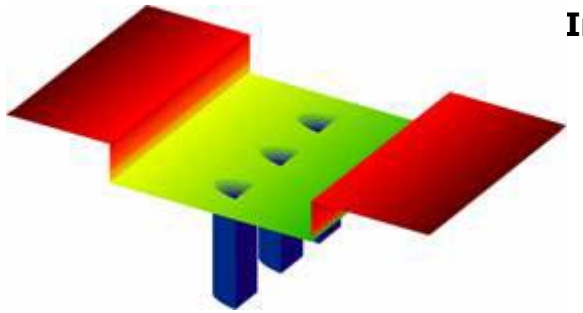
Quantum Dot Infrared Photodetectors (QDIPs)

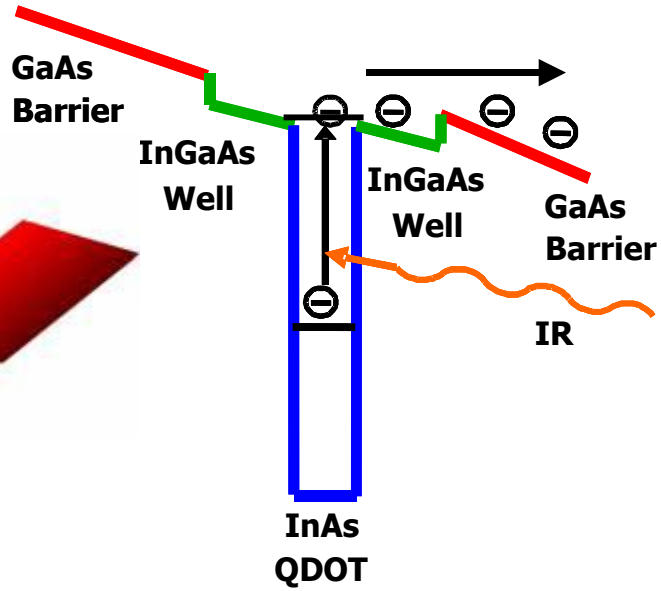


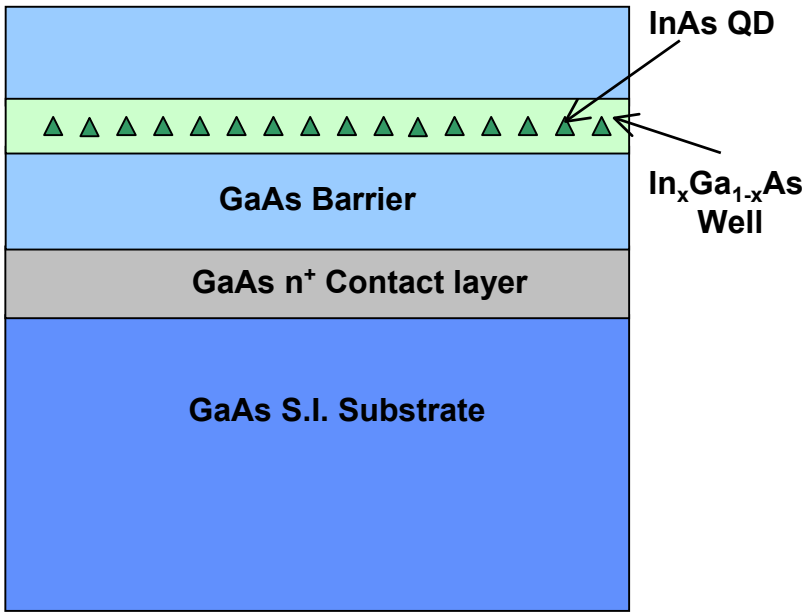
- InAs quantum dots (QDs) embedded in GaAs matrix
- Quantum dots act as infrared absorbers
- Dot size and doping adjusted for optimum response
- Multiple stacks of QD layers grown to boost quantum efficiency
- Photoconductor
  - Unipolar device, n^+ contacts.

Dot-in-a-Well (DWELL) QDIP



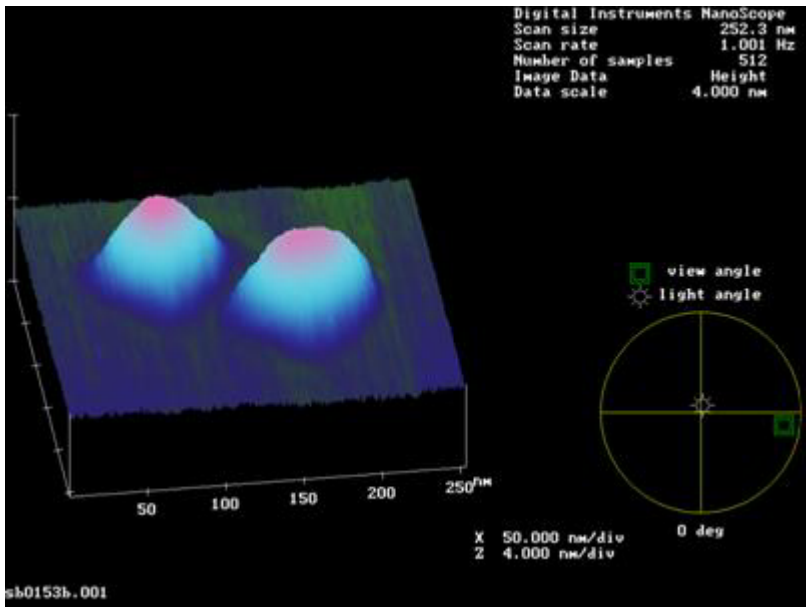






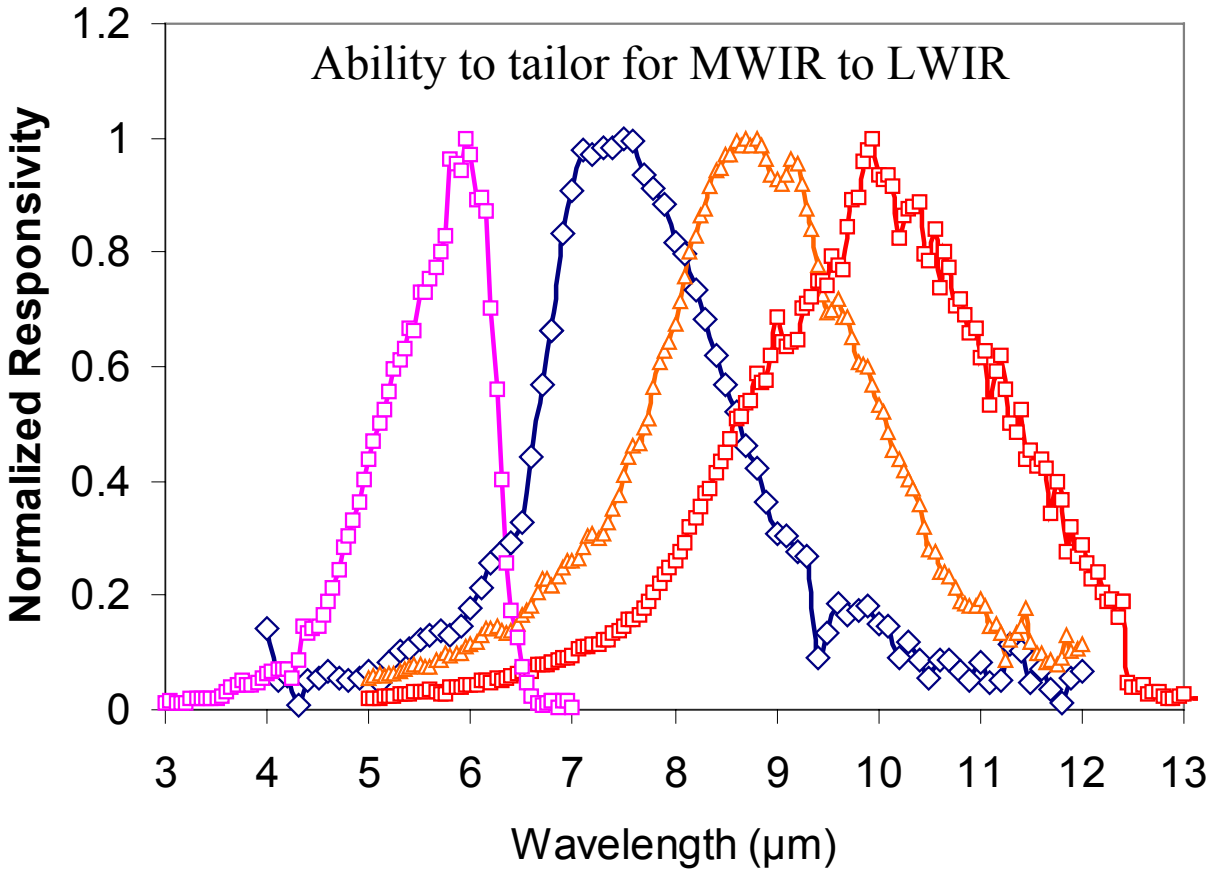
- Embed InAs dots in InGaAs quantum wells
- Motivation: Precise control of quantum well width allows easy wavelength tuning

Quantum Dot Growth



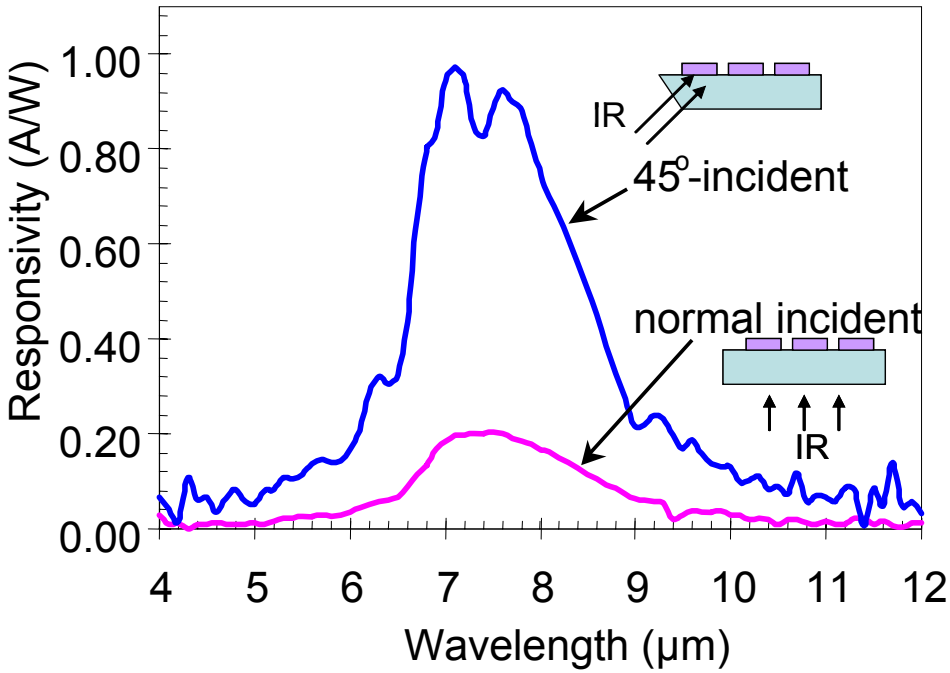
- Grown in JPL's Veeco Gen III Molecular Beam Epitaxy (MBE) machine (4 inch capable)
- Quantum dots formed by a self-assembly process
  - Deposition of semiconductor on lattice-mismatched substrate
- Typical InAs dots on GaAs are pyramidal
  - Base width ~ 20 – 40 nm
  - Height ~ 3 - 5 nm
- Over 100 wafers grown to date
  - Wafer growth time : 4-12 hours, depending on number of embedded QD stacks

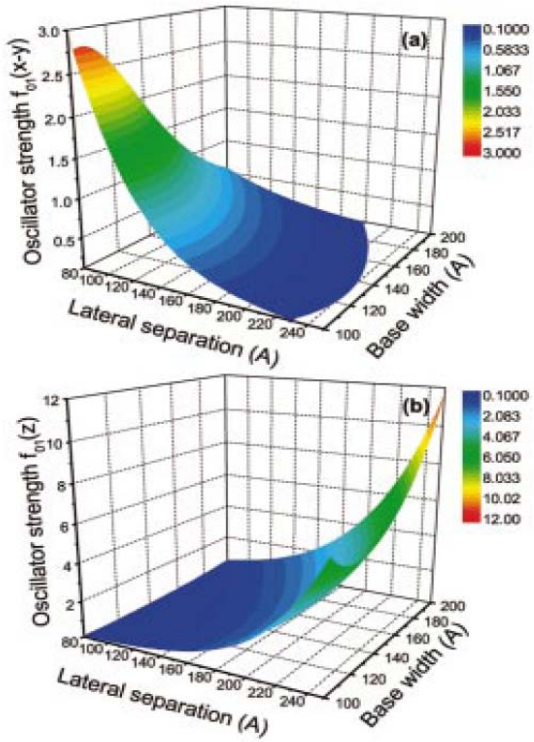
Wavelength Tuning in DWELL QDIP



- Experimentally measured spectral responsivity of DWELL QDIP
- Continuous spectral tunability via well width variation

Normal and 45° Incidence Response

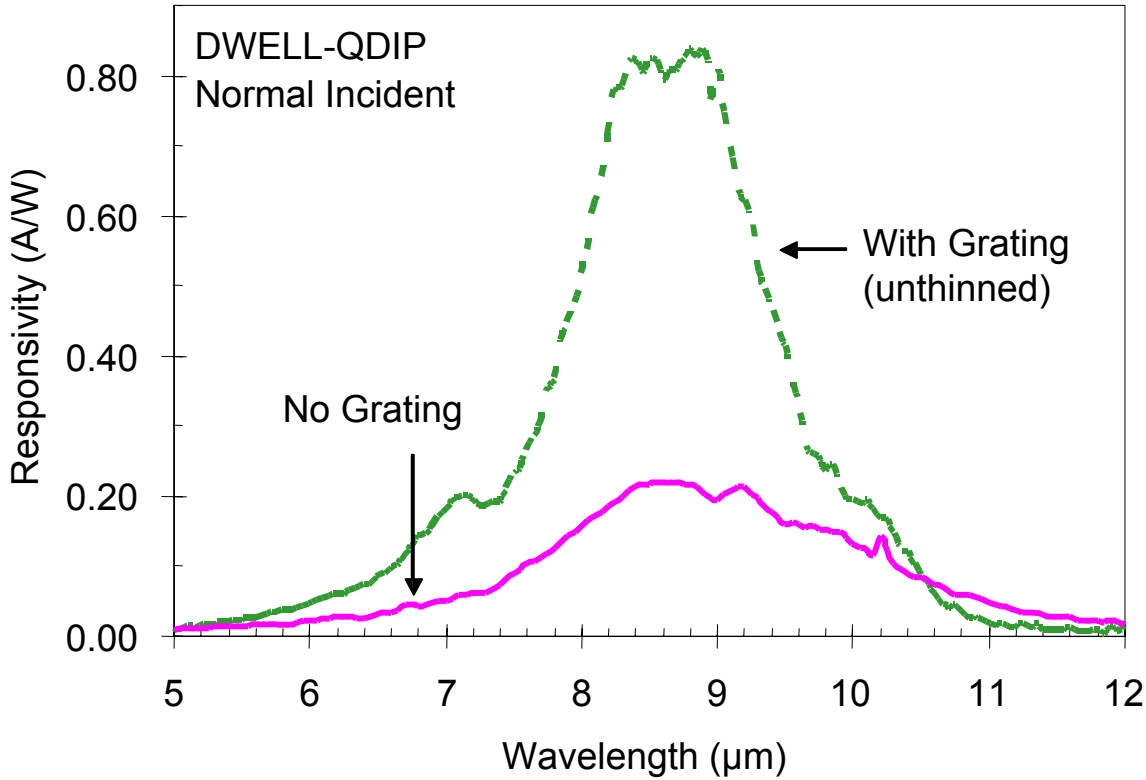




V. G. Stoleru and E. Towe, Appl. Phys. Lett., 83, p. 5026-5028, (2003)

- Much stronger normal incidence response as compared to quantum well infrared photodetectors (QWIPs)
- 45° incidence yields even stronger response
- Consistent with theoretical modeling results

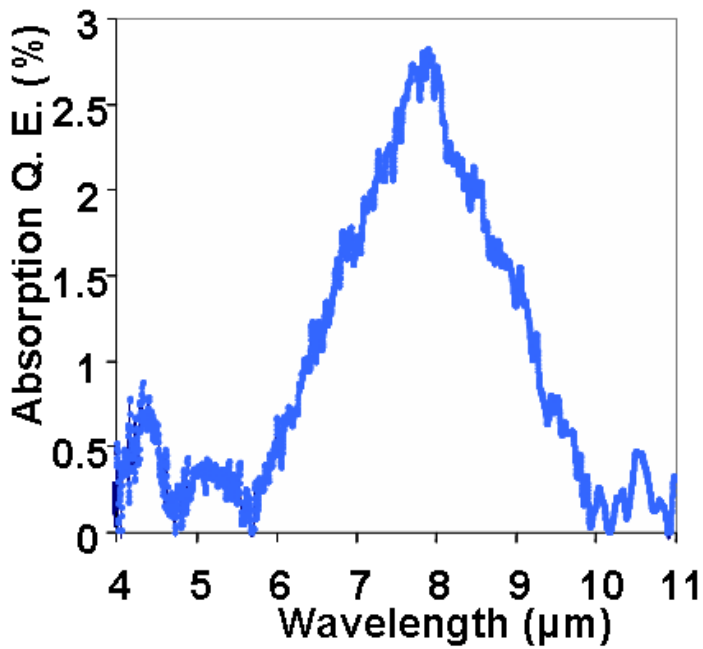
Grating Enhancement



- Observation of strong 45° incidence response led to implementation of reflection grating
- Normal incidence response now significantly enhanced by grating

Internal Quantum Efficiency

- QDIPs typically have low QE. Prior to JPL's work, only one report of QDIP QE in literature (at 0.1%)
- Internal QE of 0.67% was obtained for the initial DWELL-QDIP device through noise measurement

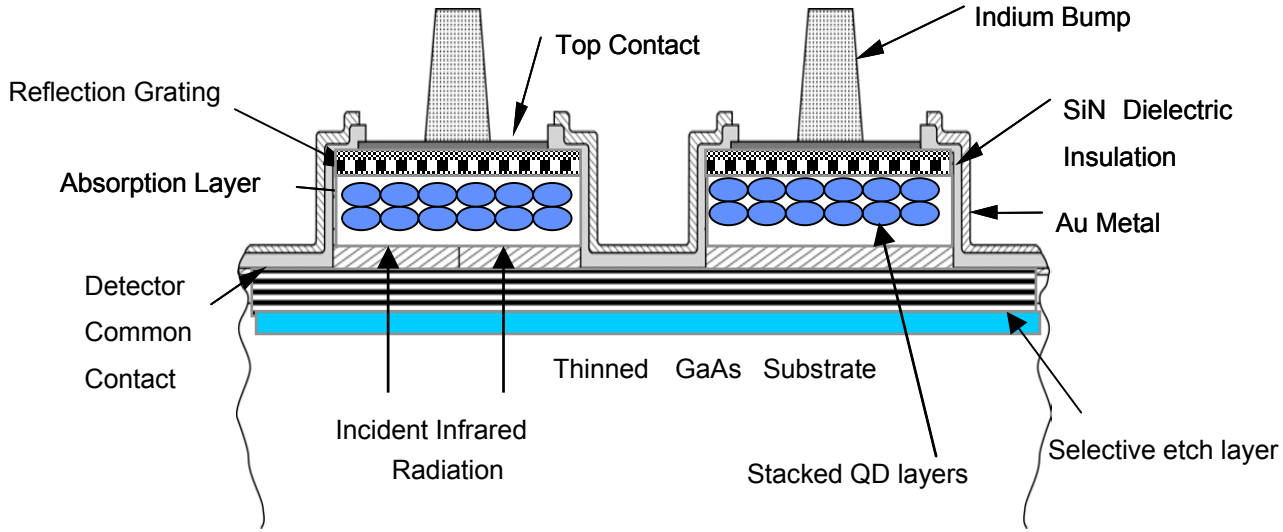


- Subsequent material improvement yielded QE= 2.8% through FTIR absorption measurement (used a 8-pass 45-degree waveguide)

Focal Plane Array Material

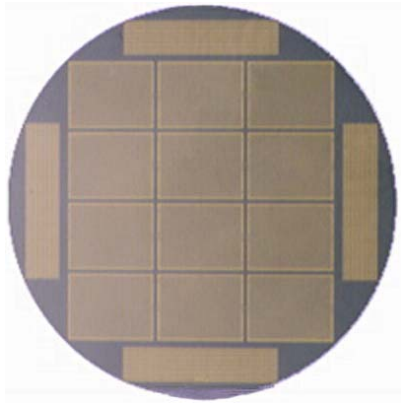
- Detector: 30-stack InAs Q-dots embedded in InGaAs/GaAs quantum wells; doping=2 e per dot; QE=2.8%.
- Integrated reflection grating structure

Veeco GEN-III 4-inch MBE machine

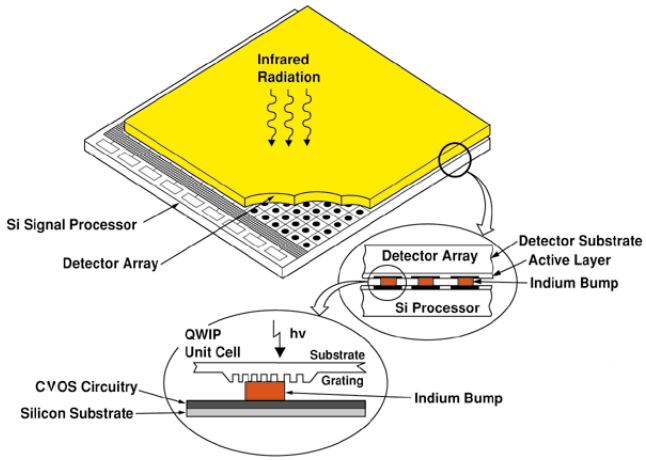


Focal Plane Array Fabrication Process

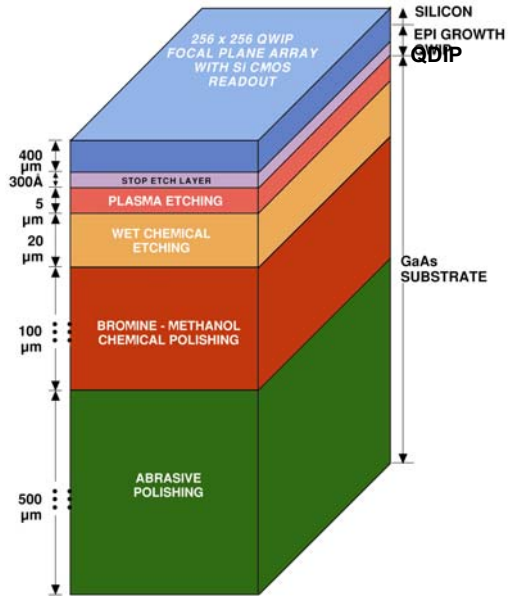
- 640x512; 25 μm pixel pitch (23 μm pixel width)
- Indigo ISC-9803 ROIC
  - direct injection, well capacity 11 million electrons



TWELVE 640X512 PIXELS QDIP FPAs ON 3-inch GaAs WAFER

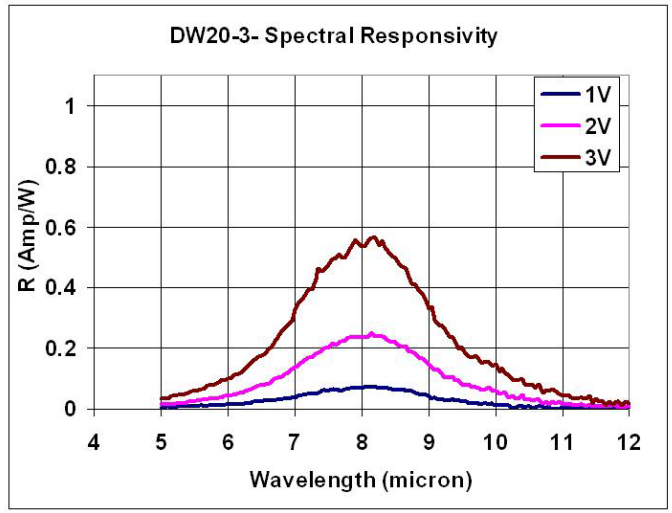


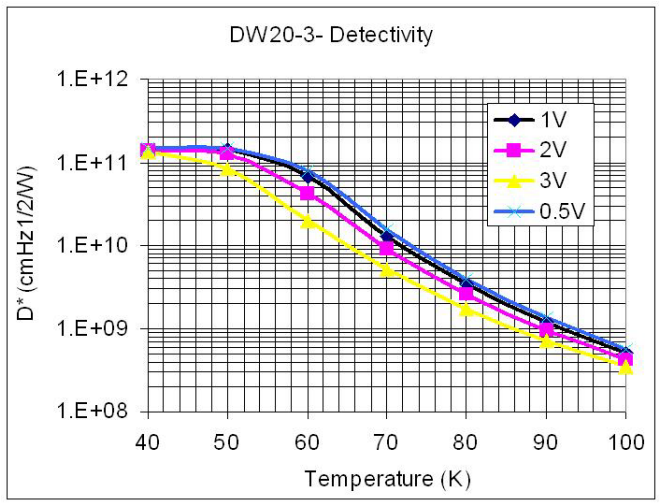
INDIUM BUMP BONDING PROCESS



FPA THINNING PROCESS

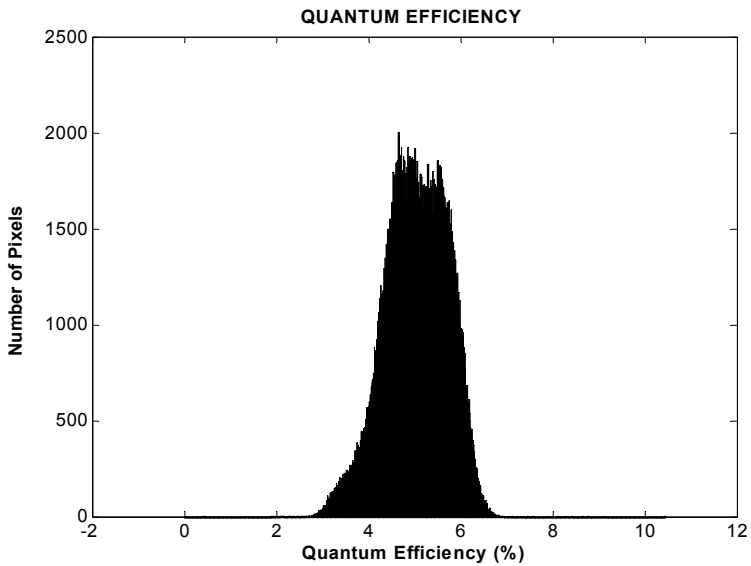
Infrared Imaging

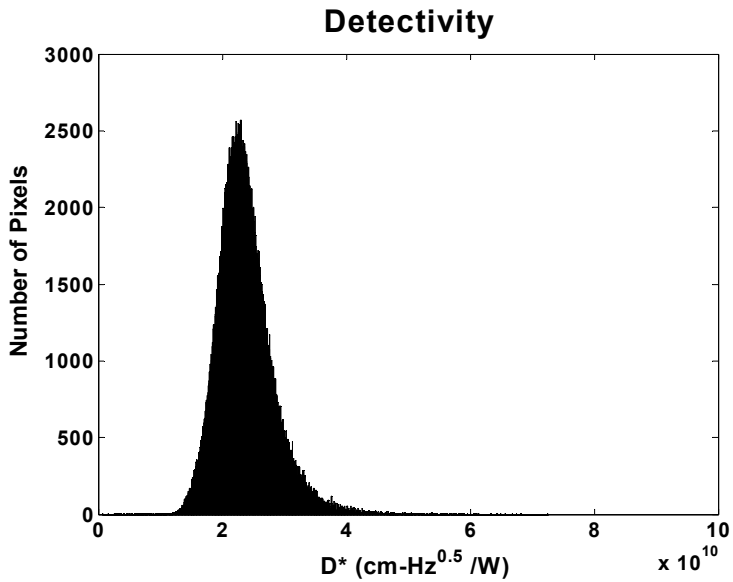




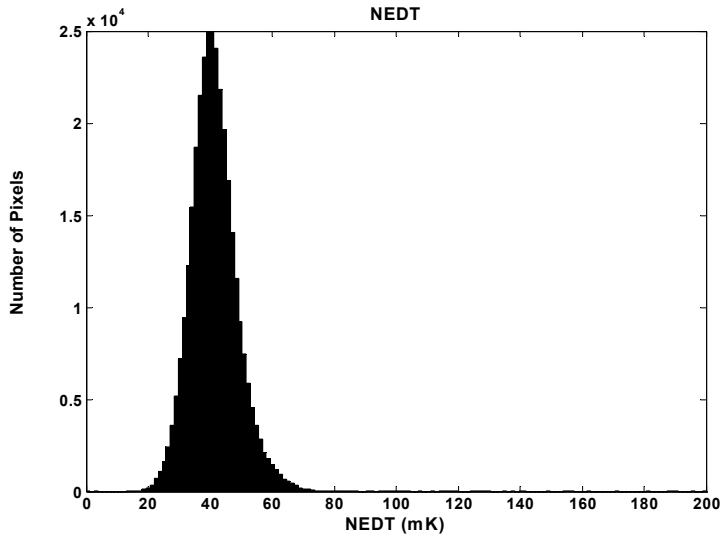
- 640x512 image taken at 60 K using f/2 optics
- Non-uniformity <0.2% (corrected); >99% operability; NEDT = 40 mK

Figures of Merit

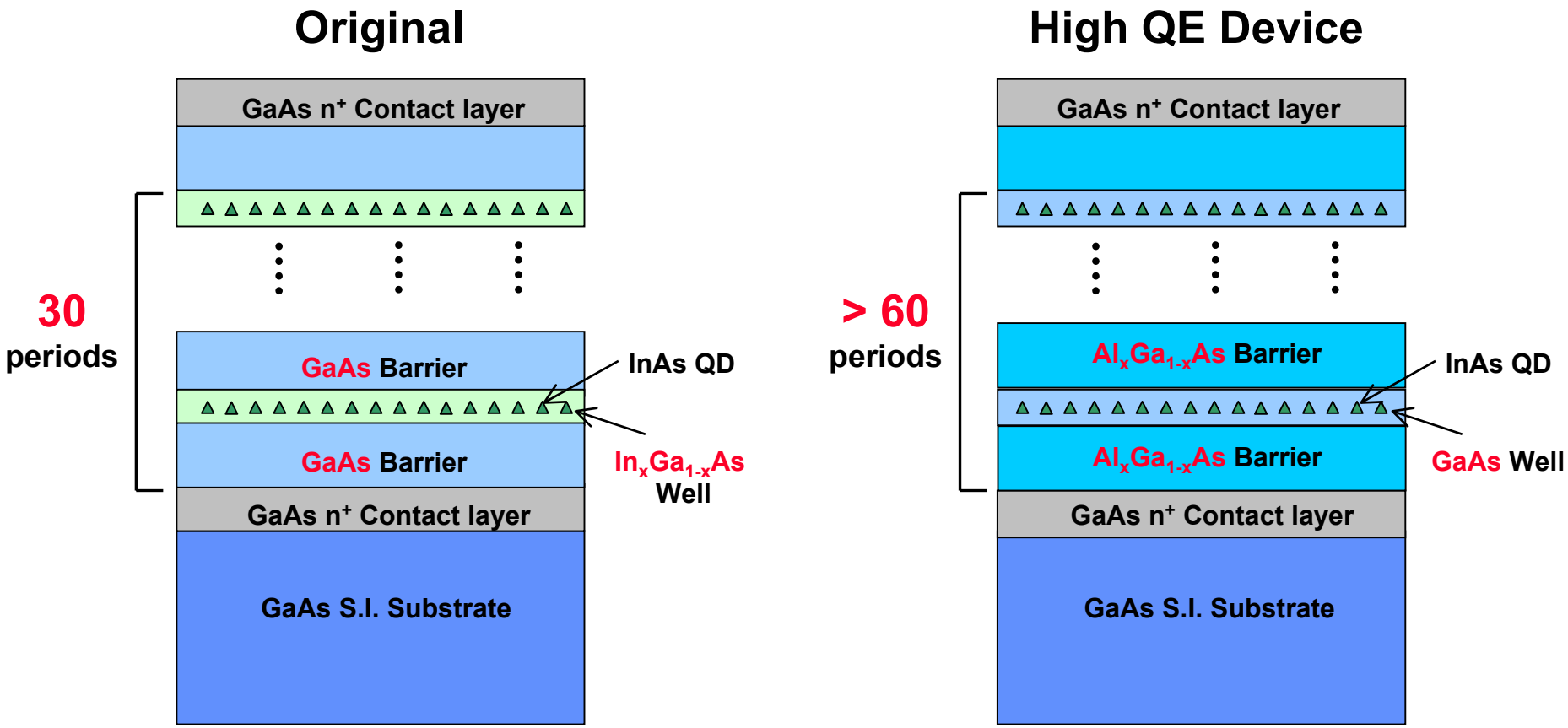




Wavelength	- 9 μm
Array Size	- 640x512
Pixel Pitch	- 25 μm
Quantum Efficiency	- 6%
Detectivity	- 2x10^{10} Jones
NEΔT	- 40 mK

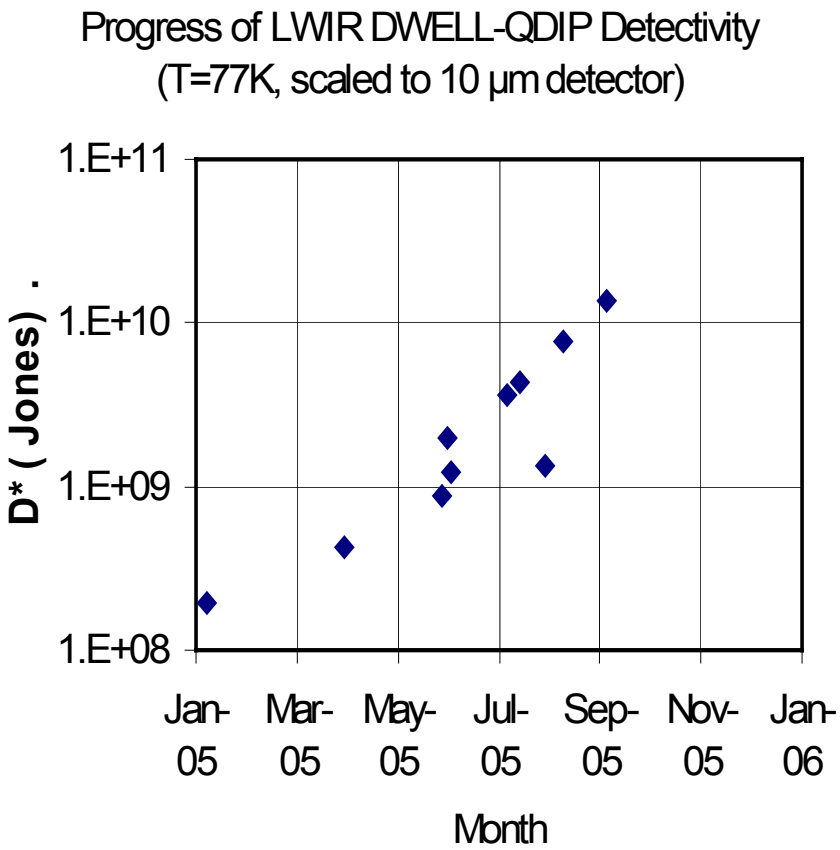


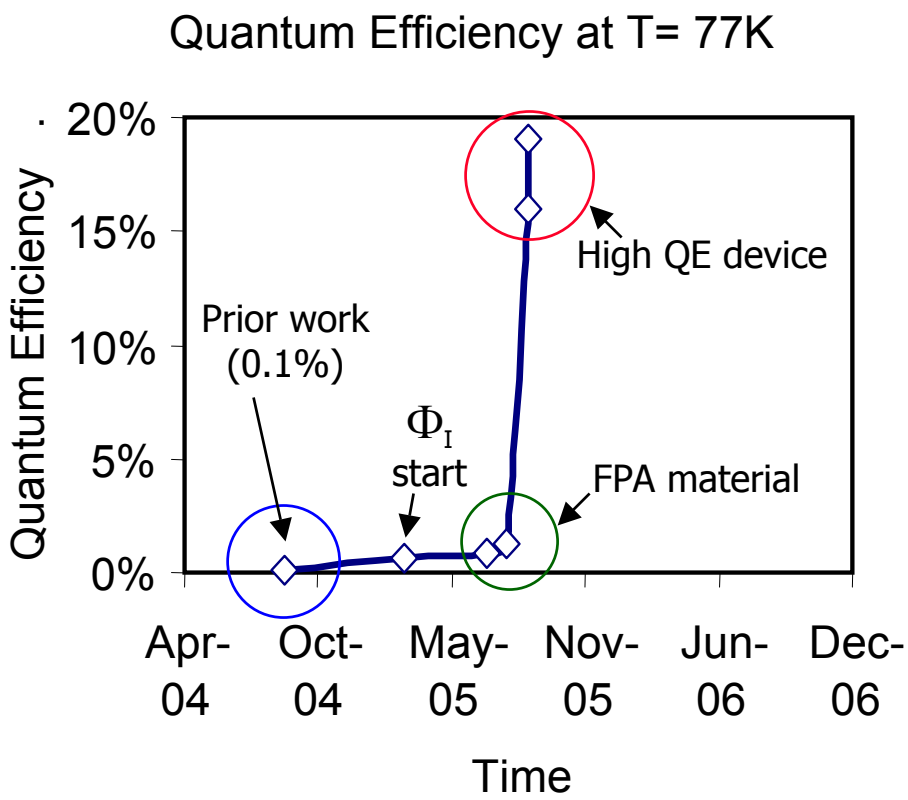
High QE Device with Enhanced Normal Incidence Absorption



- Replaced InGaAs/GaAs with superior GaAs/AlGaAs quantum wells
- Less overall strain; more quantum dot stacks
- Quantum well/dot region doping increased by factor of 10

Rapid Progress





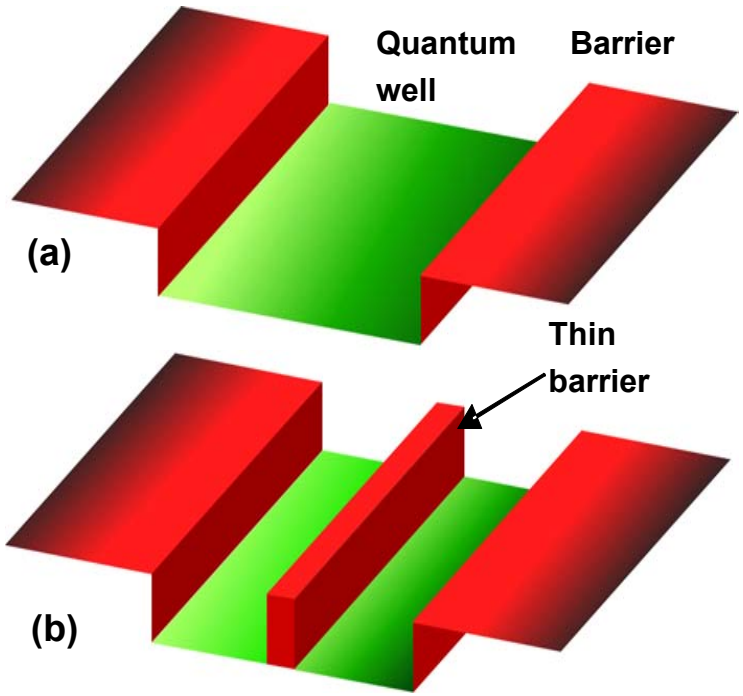
- Significant improvements in D* and QE as a function of time
- D* normalized to 10 µm for ease of comparison

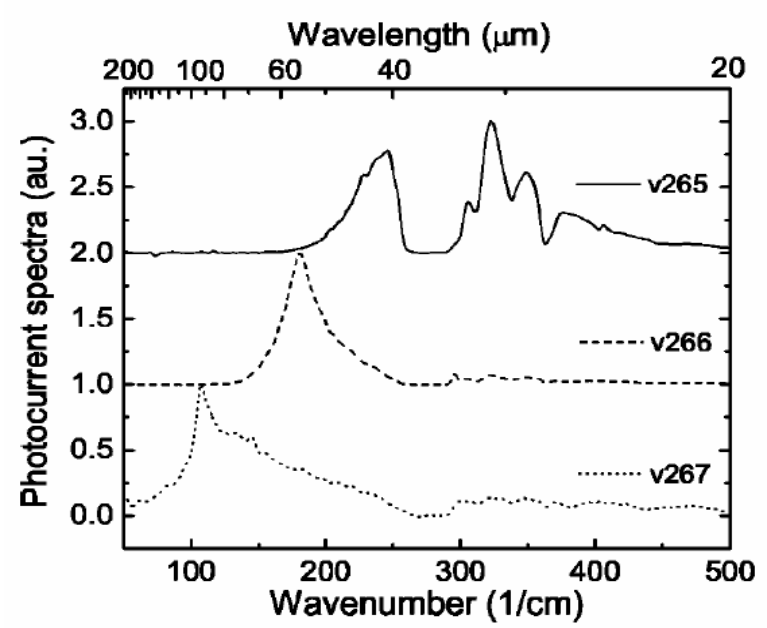
Highlight of Accomplishments

- Highest quantum efficiency (QE) obtained in a quantum dot infrared photodetector (QDIP)
  - Demonstrated 20% absorption QE
  - Highest previously reported QE=0.1%

- First large-format (640x512) QDIP based FPA
  - Highest operability (>99%)
  - Lowest non-uniformity (< 0.2% corrected)
  - Lowest NEΔT (40 mK@ 60K with 2.8% QE material)

FIR QWIPs





Normalized photocurrent spectra of three different far-IR QWIPs measured at 8K.

Illustration of proposed far-IR quantum structures: (a) Classical quantum well (b) a quantum well with a thin barrier in the center.

FIR QDIPs

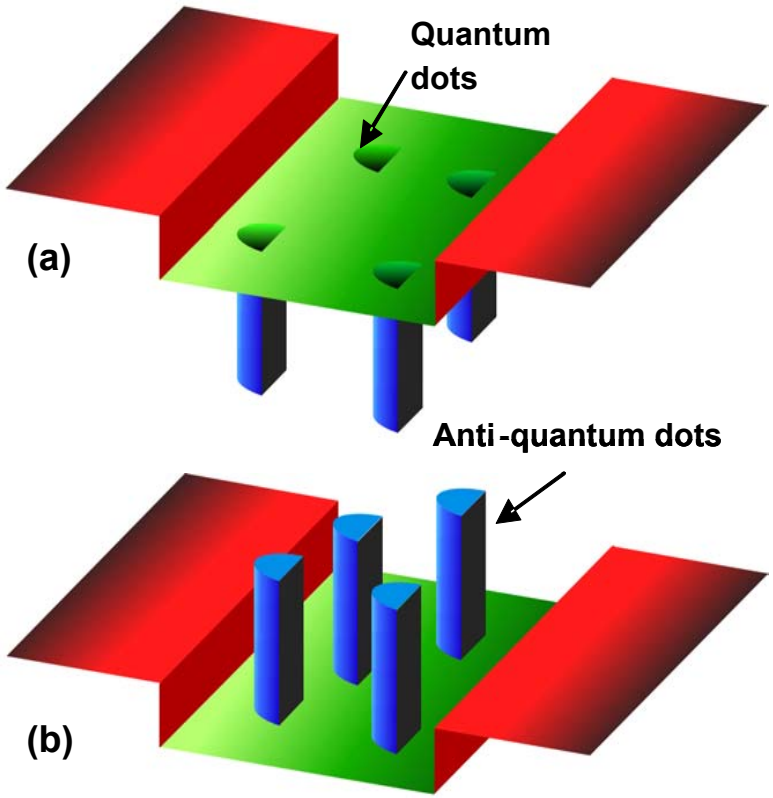
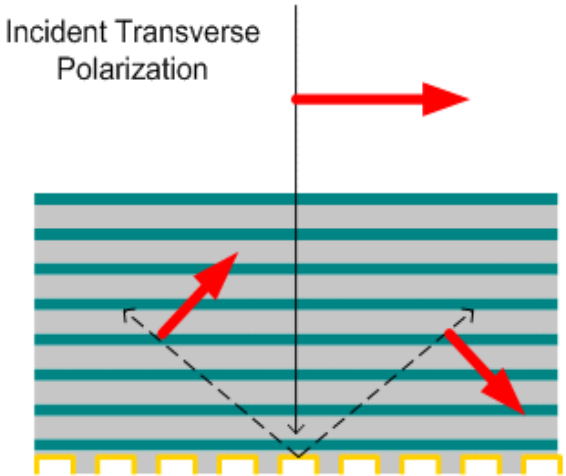
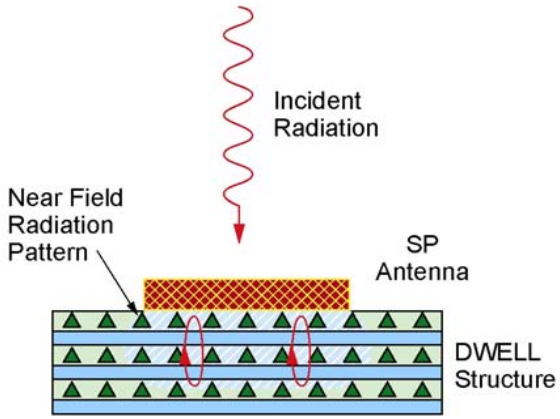


Illustration of proposed far-IR quantum structures: (a) DWELL structure (b) Anti-dot -DWELL structure.

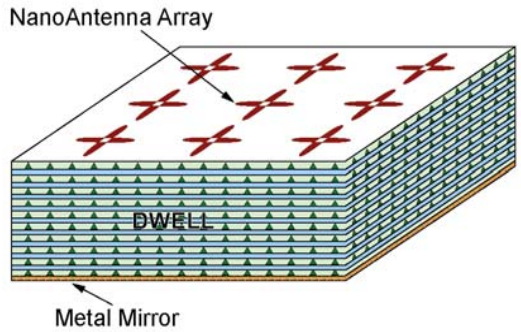
Light Coupling



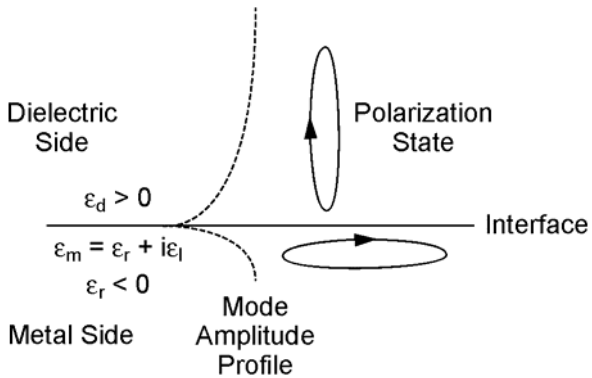
Standard QWIP Grating Coupling Structure. Longitudinally polarized components of the reflected light are absorbed by the quantum well layers. In practice, the conversion efficiency (converting the transverse to longitudinal polarization) is in the neighborhood of 30% or less.



Surface Plasmon Antenna Coupled layered structure



Representative Nano Antenna Coupled DWELL Detector Pixel.



Surface Plasmon Mode Geometry

Summary

- Many fundamental material and devices aspects of QDIPs remain to be explored and improved
  - consequently significant sustained progress is expected
  - further increases in performance will translate directly into higher temperatures of operation
- QDIP has a great potential to deliver high QE LWIR & FIR FPAs operating at high temperature
  - QE ~ 60-80%
  - LWIR Operating ~ 100 K
  - FIR Operating ~ 30 K